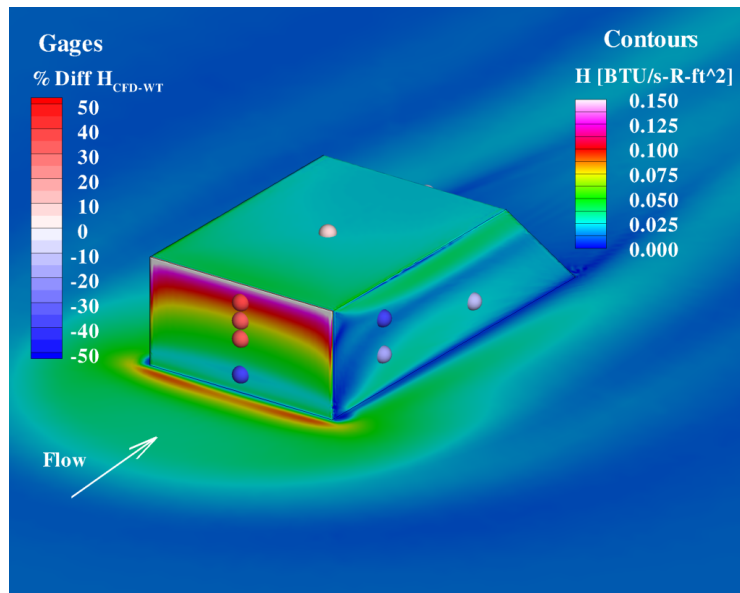


High Speed Turbulence Working Group

Lessons Learned from CFD Validation

Study of Protuberance Heating



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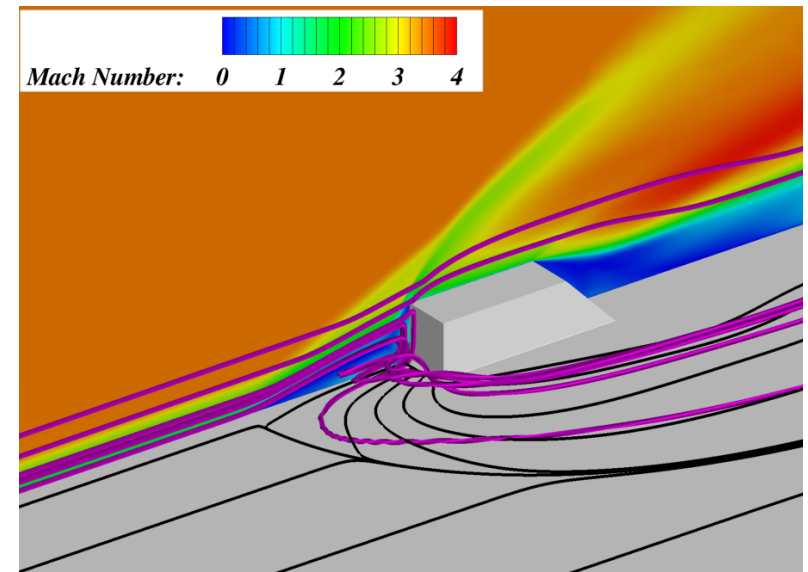
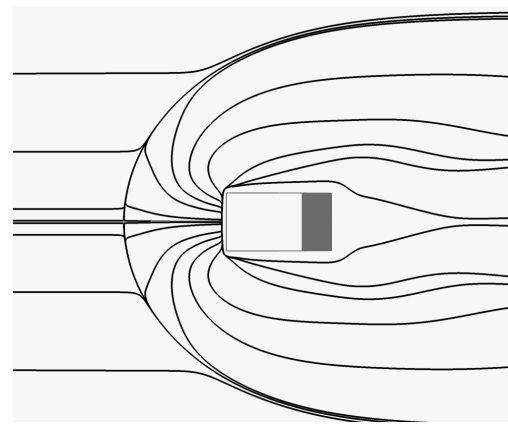
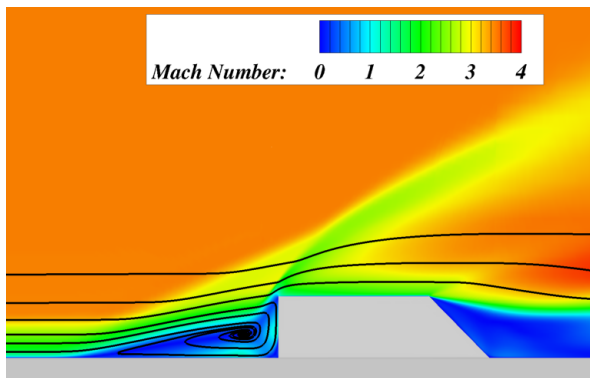
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- **Share lessons learned from a recent exercise in CFD validation of protuberance heating**
 - Impact of experimental data reduction assumptions and techniques on validation activity
 - Advanced data reduction techniques may provide useful data from non-typical test methods
 - Significance of the recovery factor for high-speed flows
- **Show typical results of the Lag turbulence model on protuberances**
- **Introduce and inform the listener of a protuberance heating dataset which will soon be available for comparison**

- **Objective of present work is to assess the accuracy of heating solutions on 3D protuberance flows**
 - 3D protuberance geometry provides a stiffer test than simple unit problems, but are less complicated than flight-relevant cases
 - Recently acquired wind tunnel data is available to aid in the analysis
 - Front-face of protuberance perpendicular to flow, with the height being just above the height of the incoming boundary layer
- **CFD run with the OVERFLOW code using the Lag turbulence model**
 - Our previous work indicated that Lag performed the best at predicting separation in plan compression ramps

Mach 3.5 Freestream:



- **Test objectives:**

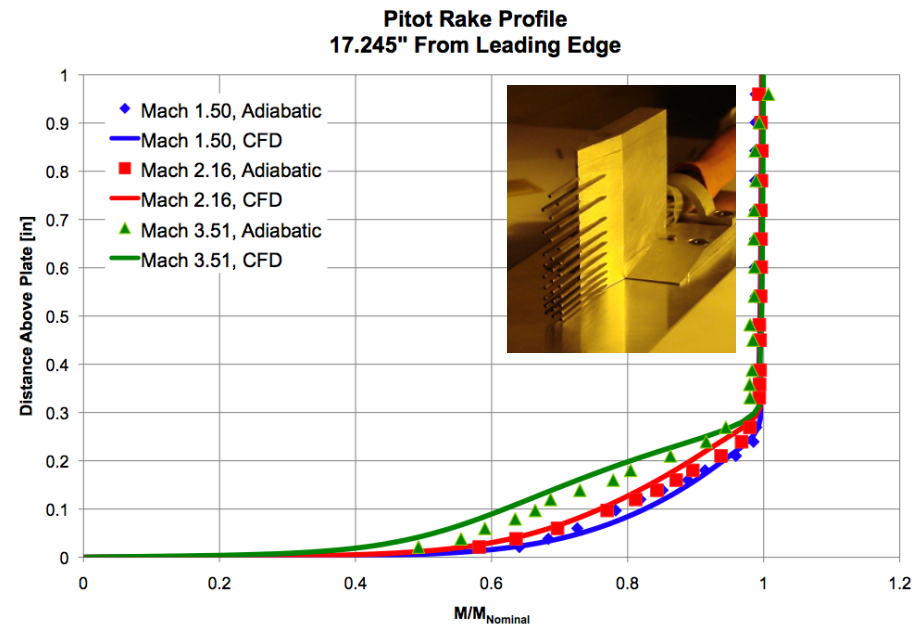
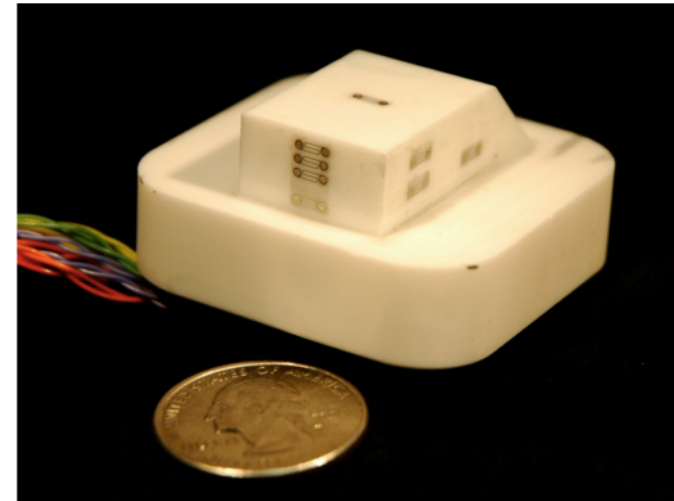
- Duplicate and extend 60's era test which is used for ET protuberance environments
- Obtain heating data useful for CFD model validation

- **Geometry and Conditions:**

- 11 different Macor protuberances on a flat plate
- Mach numbers of 1.5, 2.16, 3.51
- Reynolds number $\sim 5 \times 10^6 \text{ ft}^{-1}$
- Protuberances in turntable to permit crossflow variation
- Boundary layer tripped at plate leading edge (grit)

- **Instrumentation:**

- Thin-film gages
- IR thermography
- Limited surface pressure measurements
- Boundary layer rake
- Freestream measurements in test section near protuberance models

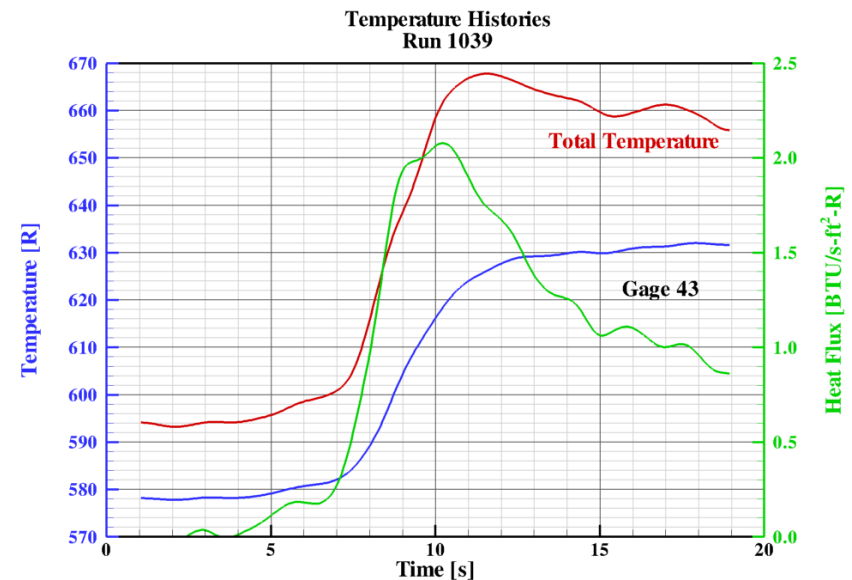
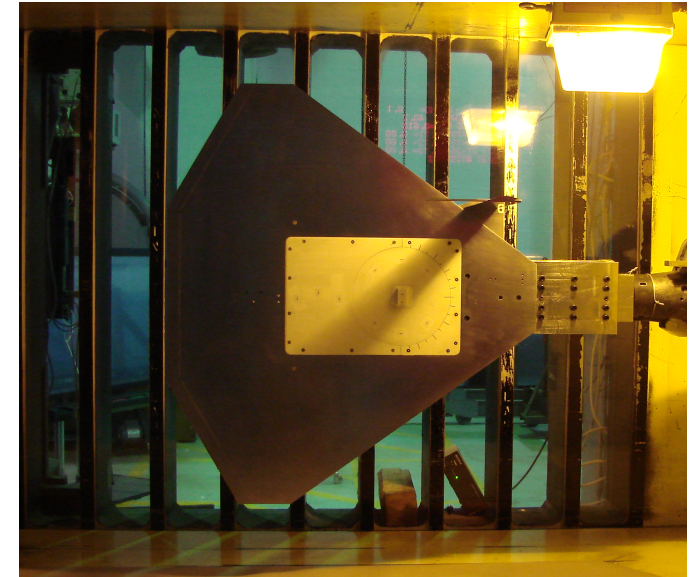


• Run Technique:

- Closed-circuit tunnel w/o injection mechanism
- Model exposed to flow at steady conditions to heat soak until in thermal equilibrium
- A 'heat pulse' was initiated in the tunnel which increased the total temperature, driving heating which was measured by instrumentation over 15-30 seconds
- Tunnel allowed to cool down and model soaked for next run
- Post-test, the measured surface temperatures were reduced to time-histories of heat flux using the Cook-Felderman 1D reduction method

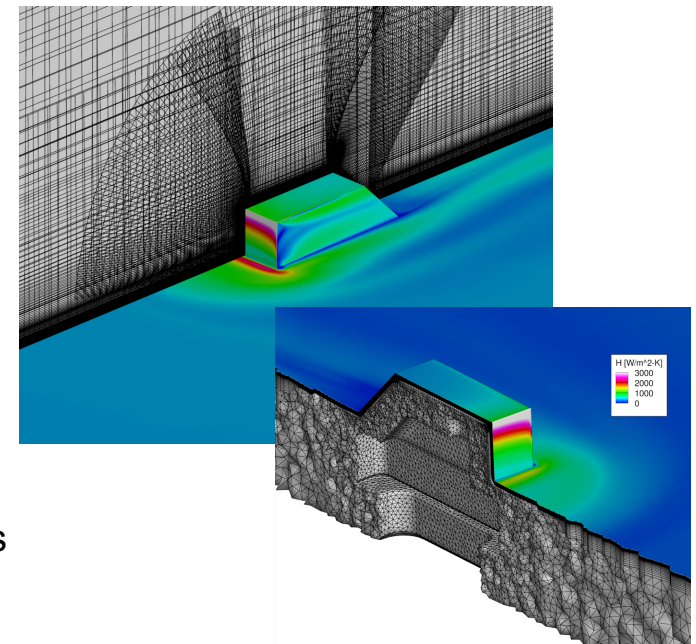
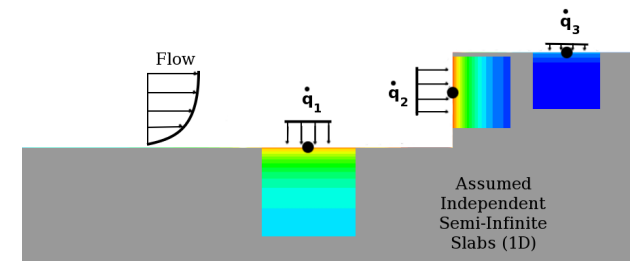
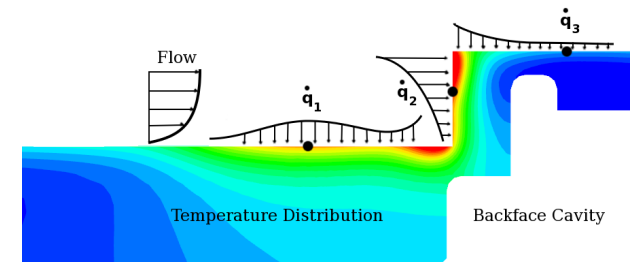
• A considerable amount of effort has been directed at making sure this data is reduced correctly

- Planning, execution, and analysis of the data has extended >4 years
- Although it is a very complicated dataset, a significant amount of effort has been put into reducing, understanding, and correcting the data.
- It is nearly in a form that can be used for CFD validation.



Mach 2.18

- Long run times and small model sizes bring into doubt the 1D conduction assumption used to reduce thin-film temperatures to heat fluxes
- A thermal analysis technique was developed to introduce '3D conduction errors' into CFD predictions in order to compare to test data on similar terms
 - CFD predictions of recovery factor and heat transfer coefficient are used to drive a thermal simulation of the wind tunnel run
 - The results of thermal analysis are reduced from temperature to heat flux just like the tunnel data, introducing the same errors
 - These numbers can be meaningfully compared
 - Method cannot be used to 'correct' the tunnel data, as it is dependent on an un-validated CFD result
- Currently developing a simplified 3D inverse heat conduction capability to eliminate the need for the CFD computation of heating and recovery factor distributions
 - Trends from this and other protuberance heating tests will define distribution shapes, and the inverse code will scale the distributions appropriately to match the test data



- The recovery factor was found to be a particularly important parameter

- Non-uniform thermal conditions necessitates reducing data to heat transfer coefficient:

$$H = \frac{q''_w}{T_{rec} - T_w}$$

- The recovery factor in the protuberance flowfield was observed to vary in space

$$r = \frac{T_{rec} - T_{edge}}{T_o - T_{edge}} \quad r \approx \frac{T_{rec}}{T_o}$$

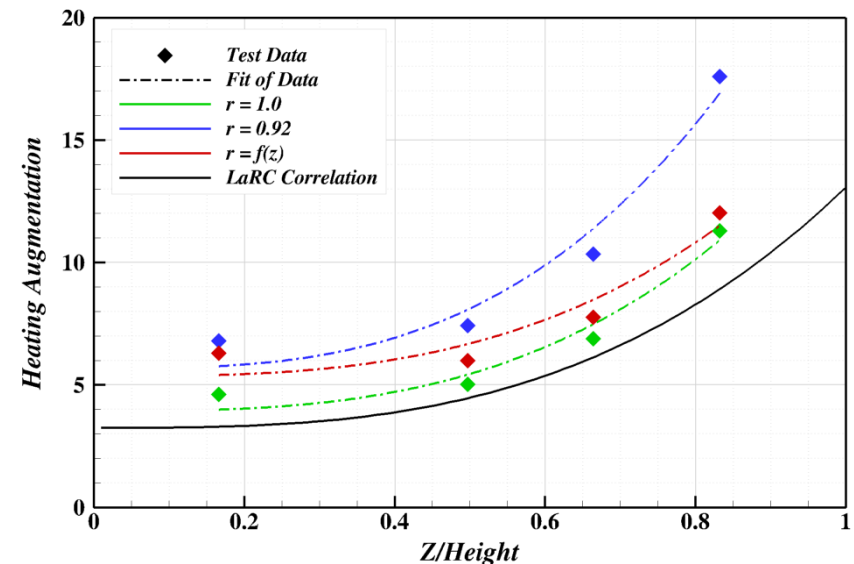
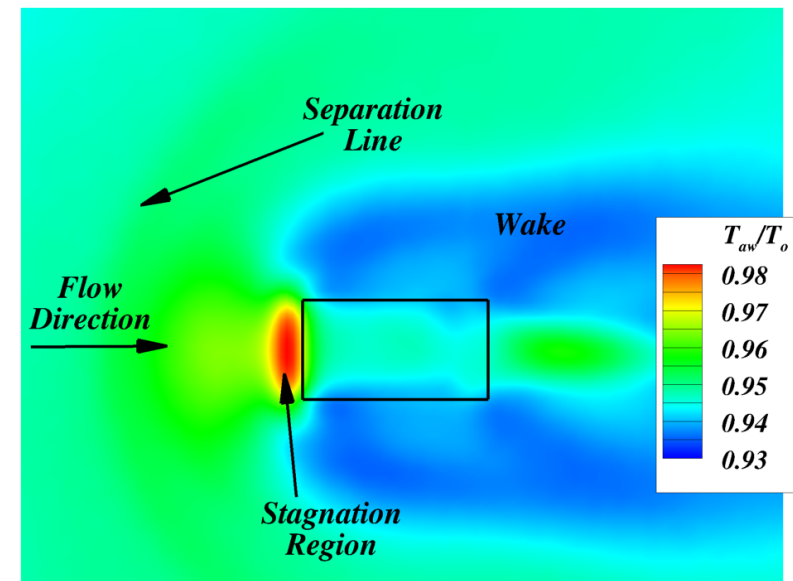
- The low driving potential makes the resulting heat transfer coefficient particularly sensitive to the assumption of recovery factor used

- The model begins the run with T_w very near T_{rec}
- The heat pulse only increased T_o by ~10%

- Given observation of varying recovery factor, data reduction from conventional tunnels becomes more difficult

- Heat flux is only half the story

Mach 2.16 Protuberance Recovery Factor

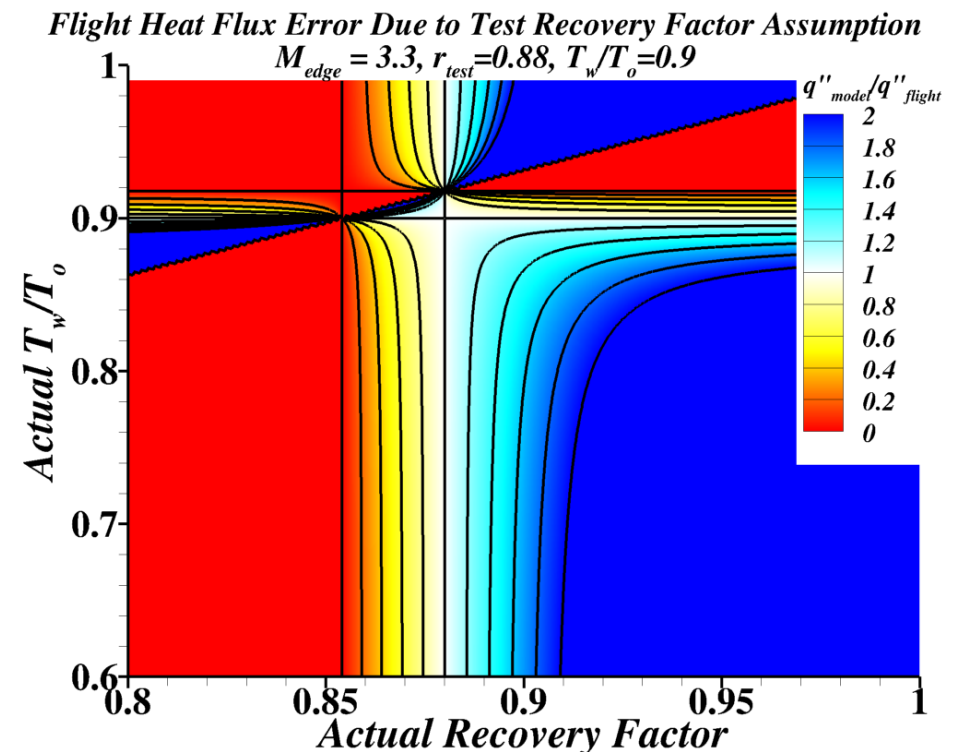


- Subsequent work on launch vehicle ascent environments indicated that similar conditions actually exist in ascent flight environments

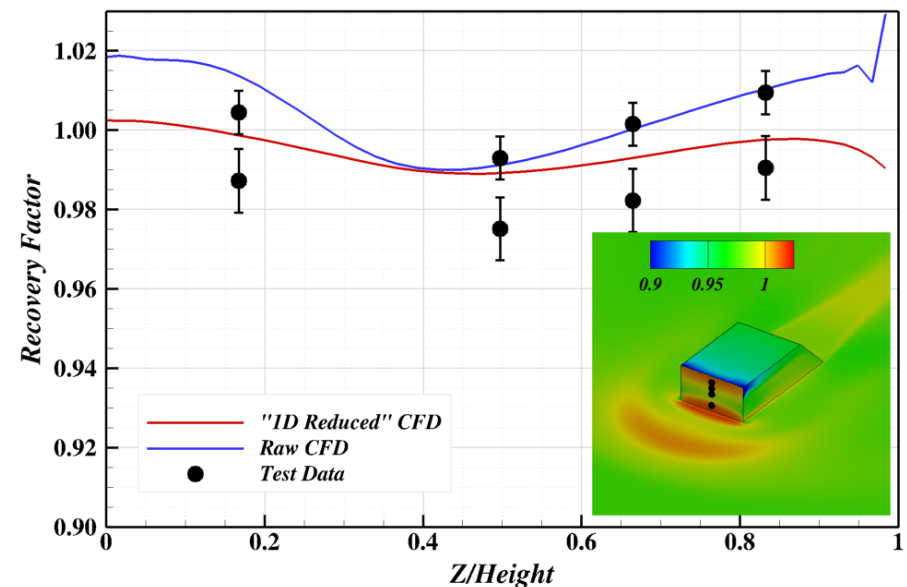
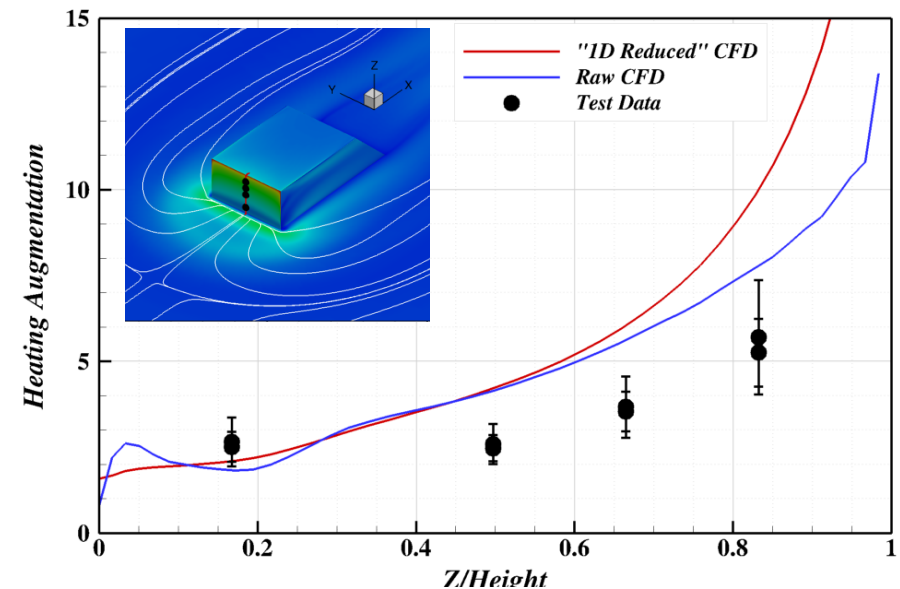
$$H = \frac{q_w''}{T_{rec} - T_w}$$

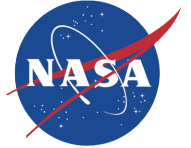
$$r = \frac{T_{rec} - T_{edge}}{T_o - T_{edge}}$$

- Relatively low freestream enthalpy & high surface temperatures (due to effective TPS materials) yields flows with low driving potential
- High edge Mach numbers yields flows with significant contributions to the total temperature from kinetic energy
- When the kinetic contribution to the recovery enthalpy is of the same order as the driving potential, the recovery factor will be important for scaling to flight
- Must make recovery factor assumption twice:
 - Reducing test data
 - Computing flight heat flux
- In much of the work I've come across to date, it does not appear that this factor is regularly given much thought



- **CFD generally over-predicts heating**
 - Consistent trend across the Mach number range and protuberance geometries run
 - This observation is consistent with other work using the Lag turbulence model
- **CFD predicts recovery temperatures in excess of the freestream total temperature**
 - Adiabatic wall boundary conditions
 - Approximate recovery factor formulation
 - Trend is consistent with other work
- **Conduction errors have not been removed from the data yet**
 - Estimate of conduction error given by difference between 'Raw' and '1D Reduced' lines
- **Other analysis (not shown) indicates that we may be overestimating the conduction errors**





- **Even a simple protuberance on a flat plate presents a difficult challenge**
 - Unable to obtain solid grid convergence...grids became too large for numerical stability
 - Heating estimates for 'engineering predictions' were higher than observed, especially in the highly separated region
- **Test data and analysis indicates that the recovery factor needs more attention than I think it typically gets**
 - Definitely must address how to appropriately scale heat flux with wall temperature/enthalpy for design applications
 - The recovery factor could be a function of wall temperature (ie: heat-flux vs wall temperature may not be a linear relationship)
- **Shuttle/Ares Protuberance Heating test will soon have some data available for validation work**
 - Not necessarily of adequate quality for high-quality validation studies, but will be good for the studies between unit problems and real-world application
 - More advanced data reduction techniques being developed for this dataset could open the door for more heating tests in university level research facilities
- **Future work**
 - Make protuberance data available to others
 - Implement a couple algebraic turbulent heat flux models in OVERFLOW and assess performance